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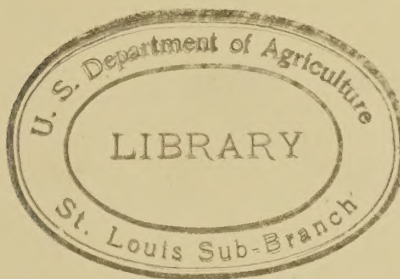
THE INDUCTION VOLTAGE REGULATOR

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Technical Standards Bulletin #9
June 5, 1943

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SUMMARY

This Bulletin contains a discussion on the use of induction voltage regulators. Methods for determining regulator ratings and suggestions for their selection, installation and protection are included. Acknowledgment is made to the various engineers of the Technical Standards Division, Design and Construction Division, and Cooperatives' Operations Division, of REA, and to the Allis Chalmers Company, General Electric Company, and the Westinghouse Electric and Manufacturing Company for their comments and suggestions.

THE INDUCTION VOLTAGE REGULATOR

On electric power systems having a variable load, the voltage at any point on the system will generally vary with load fluctuations. Almost all power systems possess approximately these characteristics. Since such voltage fluctuations at appreciable distances from the power source are usually of sufficient magnitude to present serious problems to the operation of consumer equipment, many devices have been designed for installation at strategic points so that these fluctuations may be reduced to unobjectionable proportions. Voltage regulators, in general, consist of a means for controllably varying the power system voltage, together with a voltmeter mechanism for operating the regulator so as to maintain a constant line voltage output, regardless of the variation in the input voltage. The purpose of this bulletin is to discuss one of these types, the induction voltage regulator.

I. General Principles

The induction regulator consists essentially of a transformer having a primary or shunt winding connected in parallel with the system load, and a secondary winding connected in series with the line to be regulated. The secondary winding is so arranged as to have a controllable induced voltage. The primary winding supplies the excitation for the regulator, while the secondary provides the voltage regulating function. The induction voltage regulator, unlike conventional transformers, has each winding wound upon its own separate core, with provision being made to allow the primary winding, together with its associated core, to rotate within the secondary assembly. By controlling the angular displacement of one winding with respect to the other, the variable flux linkage between the two windings provides an induced voltage in the secondary of controllable magnitude. When this secondary is inserted in series with the power source, this device will provide any desired increase (or decrease) in voltage within the range of the secondary for points on the power system beyond the regulator. Figure 1 shows the

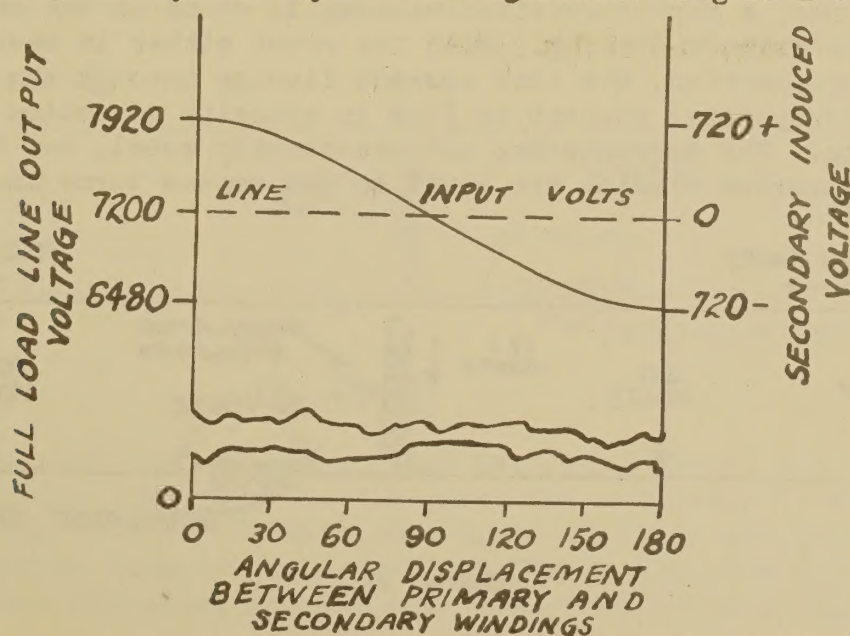


Figure 1.

relationship, at full load, and a constant voltage input between the angular displacement and (1) the line output voltage and (2) the secondary induced voltage.

Induction regulators commonly used for power systems have a voltage-regulating relay, sometimes called a contact making voltmeter, controlling a driving motor to automatically provide the rotor position necessary to have the desired output voltage. Induction regulators are often equipped with "line drop compensators." These compensators are used to maintain a nearly constant voltage at some load center on the line beyond the regulator installation.

By insertion of an impedance in series with the voltage-regulating relay, and passing a current proportional to the line current through this impedance, the potential applied to the relay will be reduced by an amount proportional to the line current. The line current itself cannot be passed through the line drop compensator impedance and, therefore, a current transformer is included in the regulator and the impedance connected across its secondary. By properly proportioning this impedance to the instrument transformer ratios and the line impedance between the regulator and the load center, the voltage applied to the relay may be reduced by an amount equal to the voltage drop between the regulator and the load center, providing no appreciable part of the load is taken from the line between these points. Since the voltage applied to the control mechanism is, under the above conditions, equal to the system voltage at the load center, the regulator will provide a constant voltage at the load center. Line drop compensator adjustment is provided on the regulator control panel to provide for various line impedances.

Although fundamentally a transformer, an induction voltage regulator will have higher core losses than a static transformer of equivalent capacity due to the air gap which must exist between the primary and secondary winding cores. In order to equalize the losses and the reactance for various rotor positions, a short-circuited winding is wound on the rotor at right angles to the primary winding. With the rotor either in maximum raise or maximum lower position, the line current flowing through the series winding causes a corresponding current to flow in opposite direction through the shunt winding. The currents are not necessarily equal, but the ampere turns in the series winding are equal to the ampere turns in the shunt winding.

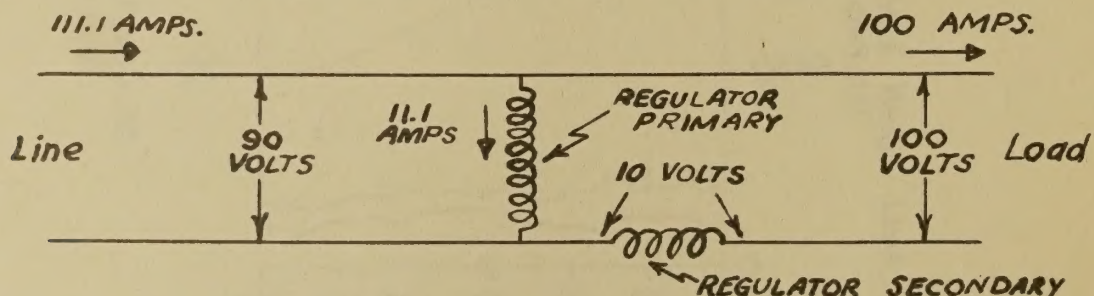


Figure 2.

When the rotor is at some angular displacement with respect to the stator, some of the ampere turns of the series coil will be unopposed by the ampere turns of the shunt coil due to the angular displacement of one coil with respect to the other. As a result, the reactance of the series coil is increased, thereby opposing the flow of line current through it. To prevent this, a short circuited winding is placed on the rotor at an angle of 90° to the shunt winding. The ampere turns built up in the short circuited winding oppose the unbalanced ampere turns of the series winding, in that manner keeping down its reactance. The current in the short circuited winding varies with the angle between the primary and secondary. Sufficient copper is used in the short circuited winding, so that the total losses in the regulator remain constant throughout the entire range of regulation.

The general operation of an induction regulator may be illustrated by referring to Figures 2 and 3. (For purposes of discussion, a perfect regulator, i.e., no losses, is assumed.) Suppose that it is desirable to maintain a constant voltage of 100 volts on a load drawing 100 amperes, at unity power factor, while the input voltage varies from 90 to 110 volts. Figure 2 represents the condition of low line voltage.

For this condition, the voltage-regulating relay will adjust the position of the rotor so that the induced secondary voltage will be 10 volts additive to the line voltage making the output voltage the required 100 volts. To accomplish this, the primary will draw 11.1 amperes at 90 volts (1 KW) from the generator and this will be transferred to the secondary, appearing as 10 volts at 100 amperes (again 1 KW). In this case, where the supply voltage is lower than the output voltage, it will be noted that a current is taken from the generator by the primary winding, and the energy (minus losses) is supplied to increase the output voltage.

The second condition, that in which the input voltage is greater than the desired output voltage is illustrated by Figure 3.

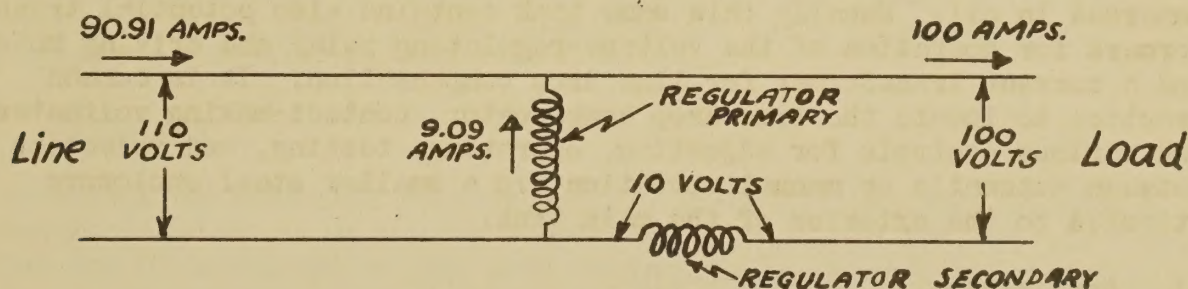


Figure 3.

As under the condition of low voltage described above, the voltage-regulating relay will adjust the rotor to that position necessary to maintain the desired 100 volt output. In this case again 10 volts are induced in the secondary but of such character as to subtract from the line voltage. This means that the secondary winding will absorb 10 volts at 100 amperes (1.0 KW)

which will be supplied to the load by a current of 9.09 amperes at 110 volts (also 1.0 KW) flowing to the load from the primary winding and permitting a corresponding reduction of input current. Thus the induction regulator will, when supplying a load at a voltage lower than the input voltage, absorb energy in its secondary which is supplied to the load as a current flowing from the primary winding.

Commercial induction voltage regulators intended for outdoor installation on power systems are commonly supplied as a single unit, including the various auxiliaries. The rotor consists of a laminated steel core, cylindrical in shape, with slots in its surface parallel to the axis in which the windings are placed. In a single phase regulator the primary winding is located in one group of slots while the short circuited winding mentioned above is wound in a second group. These windings are so located with respect to each other and with respect to the core that their planes are mutually perpendicular and the intersection of these planes coincides with the axis of the rotor. Three phase regulators use a similar core having three groups of slots for the windings so located as to have the planes of the windings at an angle of 120° with each other and their common intersection coincidental with the axis of the rotor. One winding is used for each of the three phases, and due to the distribution of these windings, no short-circuited coil is necessary. The secondary winding (or in a three phase regulator, three windings) is wound in slots in the stator which consists of a laminated steel core having through its center a cylindrical hole in which the rotor is inserted. The winding slots are located in the cylindrical surface and parallel to the axis of the rotor. A shaft passes through the center of the rotor and bearings are provided to permit the rotor to rotate freely within the stator. A gear is located on one end of this shaft so that the rotor may be turned through a gear reduction (usually a worm gear) by a small motor. The operating voltage for this motor is supplied through a motor control relay operating in response to the contact-making voltmeter and which will cause the motor to move the rotor in the proper direction to correct the output voltage. The cores, windings, and driving motor are located in a steel tank and immersed in oil. Usually this same tank contains also potential transformers for operation of the voltage-regulating relay and driving motor, and a current transformer for line drop compensation. It is common practice to locate the line drop compensator, contact-making voltmeter, and various controls for adjusting, operating, testing, and selection between automatic or manual operation, in a smaller steel enclosure attached to the exterior of the main tank.

II. Application

As applied to rural power distribution systems, induction voltage regulators will, in general, find three applications, (1) substation voltage regulation, (2) feeder voltage regulation, (3) regulation of voltage at important loads.

Rural power systems buying energy wholesale quite often find serious voltage regulation problems at their power source, especially where

they are connected to a remote end of a low voltage (often 2300 volts) urban distribution system. In such a case, the input to the rural system has the voltage fluctuation of the remote point of the urban system plus any aggravating effect which the rural system load may impose on the urban system. Such conditions may make it necessary to provide voltage correction before satisfactory service can be rendered to loads in the immediate vicinity and, in this case, voltage regulators may be incorporated into the substation structure.

Unanticipated loads at remote points on rural power systems may introduce voltage problems. Thus if a power system designed to provide adequate voltage regulation at the end of the system, has added to it a new heavy load, such as an industrial plant or a line extension, which could not be foreseen and provided for in the original design, the additional length of line or load may create serious voltage regulation problems. When such conditions occur, it will be necessary either to rebuild the line using heavier conductor, multiphase the line if single phase, or install a feeder voltage regulator. Feeder voltage regulators are usually pole or platform mounted, depending on size and number of phases, and are so located as to provide voltage correction for points on the power system beyond which voltage fluctuations become objectionable.

Certain commercial or industrial consumers may require a more nearly constant voltage than is necessary for domestic, farm, or other power uses. Under such conditions, where the voltage regulation is entirely adequate for all except the specialized use of one consumer, small voltage regulators may be installed at the transformer bank supplying this consumer to provide correction only for energy requiring this close control. When two or more regulators are placed in series in any circuit, special engineering studies should be made of the particular application to determine what, if any, interaction will take place between the regulators.

The induction regulator, in various forms, finds numerous other automatic and manual control applications which are not likely to be encountered in rural power system operation and their discussion, is therefore, not within the scope of this paper.

III. Selection

In selecting an induction regulator for a given application, it should be remembered that an induction regulator is rated, in KVA, at its transformer capacity and not at the load it is able to control. Referring again to the example illustrated in Figures 2 and 3, the regulator would be rated at that value which must be supplied by the regulator considered as a transformer, in this case, 1.0 KVA, even though the load is 10 KW. In general, the rating of the regulator may be determined by multiplying the peak load of the system beyond the regulator by the maximum secondary induced voltage expressed in percent of rated primary voltage (rated percent regulation), divided by 100. Thus, the regulator cited in the example above, supplying a peak load of 10 KVA, and being capable of

raising (or lowering) the input voltage by 10 percent would have a calculated capacity of:

$$\text{KVA Rating} = \frac{\text{KVA System Peak Demand} \times \text{Percent Regulation}}{100} =$$
$$\frac{10 \times 10}{100} = 1.0 \text{ KVA}$$

In general, induction voltage regulators for feeder use are designed for 10 percent regulation; and regulators of this rating may, therefore, have their capacity determined as one tenth of the system load beyond the regulator installation. It should be noted that the induction regulator is desired to deliver full rated percent regulation at full load and with a circuit power factor of 80 percent, and that the voltage correction which may be supplied will be altered slightly at other loads due to change in IZ voltage drop in the regulator windings.

With reference to voltage and frequency rating, regulators should never be installed on a rural system whose voltage or frequency varies more than 10 percent from the rated value. An increase in voltage or a decrease in frequency may cause difficulties due to the increase in the magnetizing current and losses. A regulator should, therefore, not experience a simultaneous increase in voltage and decrease in frequency although no difficulty should be experienced in the operation of induction regulators when operated with a simultaneous 10 percent increase (or decrease) in both voltage and frequency.

For installation on three phase lines, a choice may be made between the installation of one three-phase regulator or three single-phase regulators. The installation of a single three-phase regulator will be the least expensive and the most desirable where the various phase voltages are nearly equal at all times. Three-phase regulators utilize one voltage-regulating relay and provide voltage compensation in all phases in that magnitude necessary to correct the voltage in the phase in which the relay circuit is installed. For unbalanced voltage and load conditions on polyphase systems, three single-phase regulators are often installed to provide individual voltage control in each phase and thereby correcting the voltage unbalance. On three-phase delta systems, two regulators can be used in an open delta connection. This arrangement cannot be used on wye type systems.

IV. Installation and Care

Before any attempt is made to install, test, operate or maintain an induction regulator, the instruction manual should be read carefully. The nameplate data should be checked to make certain that the regulator is proper for the installation intended.

Regulators should be installed in accordance with the latest approved construction drawing. Banks of regulators will usually be mounted on platforms while single regulators may be either pole or platform mounted. The general circuit used for single-phase induction regulator installations is illustrated in Figure 4.

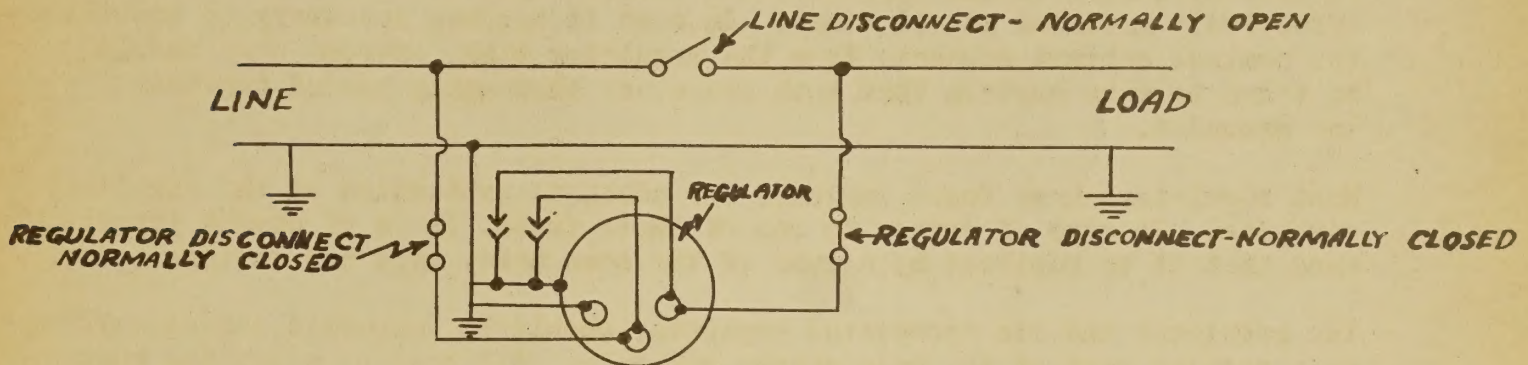


Figure 4.

This circuit is so arranged to allow the regulator to be installed or removed from the system without interrupting service. To remove the regulator from service, the following procedure should be followed:

1. Change regulator from automatic to manual operation and adjust to neutral position.
2. Close line disconnect.
3. Open regulator disconnects.
4. Remove regulator.

To place a regulator in service the reverse procedure would be followed:

1. Set the regulator for manual operation and adjust for neutral position.
2. Close regulator disconnects.
3. Open line disconnects.
4. Turn the regulator control to automatic position.

The line should be de-energized before the work is attempted, but if circumstances prevent this, all safety measures applicable to hot line work should be rigidly observed.

Polyphase regulators should not be installed or removed from service without de-energizing the power system, although banks of single-phase regulators installed on a polyphase system may be handled in the manner described above.

In order to protect the regulator, lightning arresters should be installed on the line, at the regulator location, on both sides of the regulator.

Due to the high surge impedance of the secondary winding, lightning arresters on one side of the regulator are not adequate protection unless low voltage arresters are installed across the series winding so that lightning disturbances may be by-passed around that winding to the remaining lightning arrester.

To prevent danger to the operator, the entire regulator assembly should be effectively grounded at all times. In case it becomes necessary to install the control cabinet separate from the regulator tank, extreme care should be taken to make certain that both cases are thoroughly bonded together and grounded.

Most regulators have fuses included for adequate protection of the auxiliary circuits. In case of damage to one of these fuses, it is of utmost importance that it be replaced by a fuse of the same make, type and rating.

The regulator and its associated apparatus should be inspected periodically as a regular part of the maintenance schedule. All control apparatus must be kept free from dirt and dust, and rotating parts kept well lubricated with mineral oil. The contacts of the motor control relay and the voltage-regulating relay should be inspected and any carbon deposit on them cleaned with a little carbon tetrachloride. If the contacts become pitted, the manufacturer's instructions should be consulted for the proper remedy.

Periodic adjustment of the line drop compensator will be necessary with load growth in order to maintain a predetermined voltage at the load center. This adjustment should be made a part of the regular maintenance schedule. The oil in the regulator will evaporate slowly, and refilling will be necessary from time to time in order to maintain the oil at its proper level. The insulating oil should be maintained in such condition as to test at least 22 KV under standard ASTM insulating oil test procedure.

Detailed directions for maintenance, oiling, cleaning, testing, and adjusting induction voltage regulators will be found in the instruction manual accompanying the regulator.